

Medium–separation binaries do not affect the first steps of planet formation

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ABSTRACT

The first steps of planet formation are marked by the growth and crystallization of sub–micrometer–sized dust grains accompanied by dust settling toward the disk midplane. In this paper we explore whether the first steps of planet formation are affected by the presence of medium–separation stellar companions. We selected two large samples of disks around single and binary T Tauri stars in Taurus that are thought to have only a modest age spread of a few Myr. The companions of our binary sample are at projected separations between ~ 10 and 450 AU with masses down to about $0.1 M_{\odot}$. We used the strength and shape of the $10 \mu\text{m}$ silicate emission feature as a proxy for grain growth and for crystallization respectively. The degree of dust settling was evaluated from the ratio of fluxes at two different mid–infrared wavelengths. We find no statistically significant difference between the distribution of $10 \mu\text{m}$ silicate emission features from single and binary systems. In addition, the distribution of disk flaring is indistinguishable between the single and binary system samples. These results show that the first steps of planet formation are not affected by the presence of a companion at tens of AU.

Subject headings: circumstellar matter – planetary systems: protoplanetary disks – infrared: stars

1. Introduction

Two–third of the G stars in the solar neighborhood are members of multiple–

star systems (e.g. Duquennoy & Mayor 1991). These binaries and multiple systems are often found to harbor giant planets (e.g. Bonavita & Desidera 2007).

Similarly, young low-mass pre-main sequence stars are very frequently members of multiple systems, mostly binaries (Mathieu et al. 2000; Duchêne et al. 2007). This suggests that planet formation around single stars such as our Sun may be atypical and urges us to understand the effects of stellar companions on planet formation. We tackle this question from an observational point of view. Because numerical simulations of grain agglomeration suggest short timescales for the formation of planetesimals (only a few 10^4 yr, e.g. Beckwith et al. 2000), it is crucial to know how stellar companion(s) affect the dust processing in the first few million years.

Grain growth and the settling of dust grains towards the disk midplane are thought to represent the first steps in the planet-formation process (e.g. Lissauer & Stewart 1993 for a review). The study of disks around intermediate-mass stars also indicates a link between grain growth and crystallinity. High crystallinity was found only when grains larger than the dominant sub-micron interstellar grains were present (van Boekel et al. 2005). In the context of these findings and dust evolution models (e.g. Dullemond & Dominik 2004), older disks are expected to have more processed dust (larger grains and crystals) than younger disks. In addition, their disk structure should be flatter because of the gradual settling of large dust grains towards the disk midplane. However, recent observations show that the degree of dust processing can be very different even for coeval disks around stars of similar spectral type in the same star-forming region (e.g. Przygodda et al. 2003; Apai et al. 2005). This demonstrates that dust evo-

lution is not uniquely controlled by stellar age and luminosity but at least one additional parameter is present.

There are two studies suggesting that stellar multiplicity could play a major role in the initial dust processing. Meeus et al. (2003) found that among three coeval T Tauri disks in the Chamaeleon I star-forming region the closest binary system (projected separation of ~ 120 AU) sports the strongest contribution from large ($\sim 2\mu\text{m}$) grains and has the highest crystalline mass fraction. Similarly, Sterzik et al. (2004) pointed out that the disk of a young brown dwarf with a companion at $\gtrsim 30$ AU shows more processed dust than the disk around a single brown dwarf. Although the small samples inhibit any firm conclusions, these results suggest that companions might trigger rapid dust evolution. Intuitively this may happen in different ways. A companion could speed up dust evolution by dynamically stirring the circumstellar dust grains and leading to an enhanced collision and grain growth rate (e.g. Dubrulle et al. 1995). In addition, the dynamical stirring may lead to an increased mixing that could also expose larger amounts of dust to temperatures high enough (≥ 800 K) to be crystallized.

In this paper we compare two carefully constructed samples of disks around single and binary¹ stars with a narrow age spread to test the hypothesis that binary systems have disks with more processed dust and flatter structures. In Sect. 2 we describe our samples. The data reduction of the *Spitzer* spectra and of the $24\mu\text{m}$ MIPS

¹a few of the systems in our study are triple or quadruple systems. For simplicity, we refer to the whole sample as binaries)

photometry is presented in Sect. 3. We summarize our results in Sect. 4 and discuss in Sect. 5 their implications on planet formation in single and binary systems.

2. Sample Definition

Testing whether stellar companions promote the first steps of planet formation requires: a) two coeval samples of disks around single and binary stars with precisely determined multiplicity; b) identical spectral type distributions for the two samples; c) objects in regions with no diffuse PAH emission that could contaminate the dust emission features of the targets; d) disks with faint or no PAH emission features (for the same reason as b). The Taurus–Auriga star-forming region has a reasonably complete census of its pre-main-sequence stellar population and meets best our requirements among the nearby star-forming regions. To satisfy criteria d) we selected disks around low-mass stars because they have an order of magnitude lower PAH emission than disks around intermediate-mass stars (Geers et al. 2006). The observed age distribution of low-mass stars in Taurus can be well approximated with a gaussian centered at 1.6 Myr and a spread no larger than about 2–3 Myr (Hartmann 2001). This narrow age spread minimizes any possible trend of disk evolution with age. In summary our sample of disks around single and binary stars is drawn from the Taurus–Auriga population of low-mass T Tauri stars (TTs) with circumstellar disks and ages between ~ 1 –3 Myr.

Because it is critically important to include only stars with known multiplicity, we first selected each target based on a

combination of available high-resolution imaging and interferometry, spectroscopy, and radial velocity measurements (Ghez et al. 1993; Leinert et al. 1993; Simon et al. 1995; White & Ghez 2001). In this context, we refer to a star as *single* if it has no known companions with brightness above the detection limit within $10''$ (or ~ 1400 AU at the ~ 140 pc distance of the Taurus–Auriga star-forming region). The typical detection limit of high-resolution imaging surveys is 2–3 mag fainter than the primary star in K-band, which corresponds to a very-low mass star of $\sim 0.1 M_{\odot}$ at ~ 2 Myr according to the Baraffe et al. 1998 isochrones. Only a few binary star systems have been observed with techniques reaching higher contrast (see, e.g. the discovery of a brown dwarf companion to DH Tau by Itoh et al. 2005). The typical smallest separation resolvable with the imaging surveys is $\sim 0''.1$ (~ 10 AU), meaning that a few unresolved close binaries may have been classified as single. Of these, binaries with periods < 100 days can only modestly contaminate our single star sample since their frequency in pre-main sequence stars is $8\% \pm 3\%$ (Mathieu et al. 2000). Due to the lack of general understanding of the separation distribution of close pre-main sequence binaries, it is not possible to determine the exact level of contamination. However, the required infrared excess (see below) ensures circumstellar dust within a few AU, likely inconsistent with the presence of a close stellar companion. We also excluded all known spectroscopic binaries in Taurus (Mathieu 1994; Jensen & Mathieu 1997) both from the sample of single and binary stars. Our binary sample consists of stars with companions between

$\sim 0''.1$ and $3''$ thus covering the population of medium-separation stellar companions at projected separations between ~ 14 – 420 AU. After defining the samples, we searched for available near- and mid-infrared data (Kenyon & Hartmann 1995; Stassun et al. 2001; Hartmann et al. 2005; McCabe et al. 2006; Furlan et al. 2006) to select only those targets that have excess emission indicative of a circumstellar disk. These selection criteria resulted in a sample of mostly classical TTSs for the single and for the primary star in the multiple systems. Only CZ Tau and IQ Tau in our sample are classified as weak-lined TTSs² (White & Ghez 2001; McCabe et al. 2006). The T Tauri types for the components of the binary sample are mostly classical with the exception of FX TauB, IS TauB, V710 TauB, and V807 TauB that are weak-lined TTSs (Duchêne et al. 1999; White & Ghez 2001; Hartigan & Kenyon 2003). Finally, we selected only systems with fluxes $\gtrsim 0.1$ Jy to ensure high signal-to-noise around the $10\mu\text{m}$ silicate emission feature.

Our list contains 44 sources, of which 23 are disks around single stars and 21 are multiple systems (see Tables 1 and 2). Spectral types for the stellar companion(s) are available for 18 out of 21 objects. Most companions have M spectral type (see Table 2). The single stars (or the primaries of multiple systems) are mostly between K5 and M4 spectral type. Note also that the distribution of spectral types for the single stars is almost identical to that of the primary component in multiple systems (Fig. 1). In addition,

²based on their narrow $\text{H}\alpha$ emission lines (Herbig & Bell 1988)

the fairly narrow range in spectral type minimizes any difference in the dust composition due to luminosity effects. In fact the recent study by Kessler-Silacci et al. (2006) shows that the shape and strength of the $10\mu\text{m}$ silicate features of K versus M stars are consistent with being drawn from the same population. Most of our multiple systems are binaries with separations less than $1''$ (see Table 2). Seventeen of them have circumprimary and circumsecondary disks based on the K–L, K–N colors or resolved IRAC photometry of both components (White & Ghez 2001; Hartmann et al. 2005; McCabe et al. 2006). DF Tau B and FO Tau B are the closest binary components in our sample at $\sim 0''.1$. They are also very likely surrounded by circumstellar disks based on accretion signatures like the $\text{H}\alpha$ equivalent width and the amount of optical veiling (Hartigan & Kenyon 2003). Finally, V710 Tau B and V807 Tau B have K–N and K–L colors consistent with photospheric emission suggesting that they do not have circumstellar disks (White & Ghez 2001; McCabe et al. 2006). A summary of the disk configurations is provided in column seven of Table 2. Resolved mid-infrared photometry is available for 11 out of 21 binary sources (McCabe et al. 2006). Another 8 sources have resolved L-band photometry (White & Ghez 2001), while the two closest binaries FO Tau and DF Tau have been resolved only in K-band (White & Ghez 2001). For at least two-third of the binary sample the *Spitzer*/IRS spectrum is dominated by the disk around the primary star as indicated by the near- and mid-infrared flux ratios of the primary and secondary components (column eight of Table 2). We also note that our

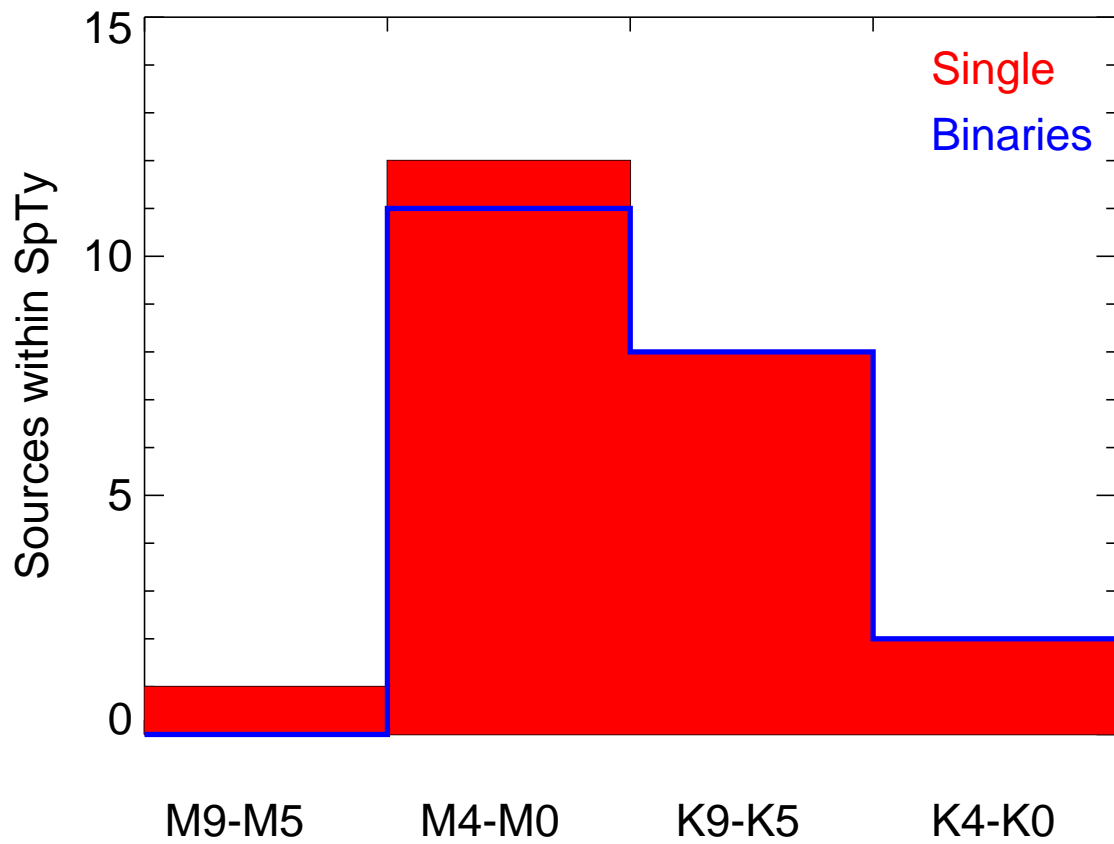


Fig. 1.— Histogram of the spectral types for the single and binary systems. The spectral type distributions of the single stars and of the primary stars in the binary sample are almost identical.

selection criteria did not exclude possibly more evolved disks such as transition disks. GM Aur and DM Tau in our list of single stars are among the best studied transition disks (see, e.g. Calvet et al. 2005).

3. Data Reduction

We use the low-resolution *Spitzer* spectra around the $10\,\mu\text{m}$ silicate emission feature to characterize the degree of dust processing in single and binary systems. Observations at wavelengths longer than $\sim 20\,\mu\text{m}$ are necessary to trace the evolution of the disk structure. For this, we prefer to use the MIPS $24\,\mu\text{m}$ photometry that is available for all (except 6) targets rather than the spectra acquired with the long-low module of the IRS, which is lacking for 14 targets. In the following we describe the data reduction of the *Spitzer* IRS spectra and of the $24\,\mu\text{m}$ MIPS photometric data.

3.1. *Spitzer* IRS low-resolution spectra

The IRS data presented in this paper have been acquired as part of the IRS/GTO program (Furlan et al. 2006) and became available to the community at the end of the year 2005. Only six of the objects we selected (CY Tau, DS Tau, FM Tau, IS Tau, V710 Tau, and V807 Tau) were observed in staring mode, with the targets placed in two nod positions along the spatial direction of the slit at $1/3$ and $2/3$ of the slit length. On all the other targets, a 2×3 step mapping observation was carried out: the three steps were chosen to be separated by three-quarters (for SL) or half (for LL) of the slit width in the dispersion direction and the two steps were separated by one-third of the slit in

the spatial direction. The exposure time at each nod position was 6 second for all targets with the exception of V710 Tau which had a 14 second exposure time per nod.

We downloaded the low-resolution IRS data that were processed with the SSC pipeline S13.2.0. Our data reduction starts from the *droopres* intermediate data product and follows the steps outlined in detail in Bouwman et al. (2007). In brief, we first subtracted the pairs of imaged spectra acquired along the spatial direction of the slit in order to correct for the background emission and stray-light. Then we replaced bad pixels by interpolating over neighboring, good pixels. Although for our analysis we use only the SL data, we also extracted the LL part of the spectra for comparison with the MIPS $24\,\mu\text{m}$ photometry where both datasets are available. Spectra were extracted from the background-subtracted pixel-corrected images using a 6.0-pixel and 5.0-pixel fixed-width aperture in the spatial direction for the SL ($5.2\text{--}14\,\mu\text{m}$) and LL ($14\text{--}35\,\mu\text{m}$) modules, respectively. The low-level fringing at wavelengths $>20\,\mu\text{m}$ was removed using the *irsfringe* package (Lahuis & Boogert 2003).

Because peak-up images were not acquired for the majority of the sources, targets may not have been positioned accurately at the center of the slit. We determined the actual position of each source during extraction by finding the peak emission of the wavelength-collapsed source profile. Once the spectra are extracted for each order, nod and cycle, we computed a mean spectrum for each order and assigned as uncertainty at each wavelength

TABLE 1
MAIN PROPERTIES OF THE SELECTED SINGLE TTSS.

#	Source	2MASS J	Adopted SpT	Ref (SpT)
S1	AA Tau	04345542+2428531	K7	1, 2
S2	BP Tau	04191583+2906269	K7	2, 3
S3	CI Tau	04335200+2250301	K7	1, 2
S4	CW Tau	04141700+2810578	K3	1, 2
S5	CX Tau	04144786+2648110	M2.5	1, 2
S6	CY Tau	04173372+2820468	M2	2, 3
S7	DE Tau	04215563+2755060	M1	2, 3
S8	DH Tau*	04294155+2632582	M2	2, 4
S9	DL Tau	04333906+2520382	K7	1, 2
S10	DM Tau♦	04334871+1810099	M1	1, 2
S11	DN Tau	04352737+2414589	M0	1, 2
S12	DO Tau	04382858+2610494	M0	1, 2
S13	DP Tau	04423769+2515374	M0.5	1, 2
S14	DS Tau	04474859+2925112	K5	1, 2
S15	FM Tau	04141358+2812492	M1	2, 4
S16	FN Tau	04141458+2827580	M5	2
S17	FZ Tau*	04323176+2420029	M0	2, 4, 5
S18	GI Tau*	04333405+2421170	K7	2, 4
S19	GK Tau*	04333456+2421058	K7	2, 4
S20	GM Aur♦	04551098+3021595	K3	1, 2
S21	IP Tau	04245708+2711565	M0	1, 2
S22	IQ Tau	04295156+2606448	M0.5	1, 2
S23	LkCa 15	04391779+2221034	K5	1, 2

*These stars have companions at projected separations just above 10'' (Hartigan et al. 1994) : DH Tau/DI Tau (15''); FY Tau/FZ Tau (16''9); GK Tau/GI Tau (12''9)

♦Known transition disks (see, e.g. Calvet et al. 2005).

NOTE.—The 2MASS source name includes the J2000 sexagesimal, equatorial position in the form: hhmmssss+ddmmss (Cutri et al. 2003).

References. — (1) Herbig & Bell 1988; (2) Kenyon & Hartmann 1995; (3) Strom & Strom 1994; (4) Hartigan et al. 1994; (5) White & Ghez 2001

TABLE 2
MAIN PROPERTIES OF THE SELECTED BINARY TTSS.

#	Source	2MASS J	Adopted SpT♣	Separation (arcsec)	Ref (SpT)	Disk configuration♠	Flux ratio (filter)♦	Ref (flux ratio)
B1	CoKu Tau3 A-B	04354093+2411087	M1	2.05	1	cp+cs	4.7 (L)	3
B2	CZ Tau A-B	04183158+2816585	M1.5	0.32	1	cp+cs	1.71 (L)	10
B3	DD Tau A-B	04183112+2816290	M3+M3	0.56	2, 3	cp+cs	1.75 (N)	10
B4	DF Tau A -B	04270280+2542223	M0.5+M3	0.09	4, 3	cp+cs	1.6 (K)	3
B5	DK Tau A-B	04304425+2601244	K9+M1	2.30	1, 5	cp+cs	8.53 (SiC)	10
B6	FO Tau A-B	04144928+2812305	M2+M2	0.15	4, 3	cp+cs	1.7 (L)	3
B7	FS Tau A-B	04220217+2657304	M1+M4	0.23	4, 3	cp+cs	5 (L)	3
B8	FV Tau A-B	04265352+2606543	K5+K6	0.72	4, 2, 3	cp+cs	2.2 (N)	10
B9	FX Tau A-B	04302961+2426450	M1+M4	0.89	1, 5	cp+cs	2.8 (N)	10
B10	GG Tau Aa-Ab	04323034+1731406	K7+M0.5	0.25	6	cp+cs	1.03 (N)	10
B11	GH Tau A-B	04330622+2409339	M1.5+M2	0.31	3	cp+cs	1.45 (N)	10
B12	GN Tau A-B	04392090+2545021	M2.5	0.33	7	cp+cs	1.53 (L)	10
B13	HK Tau A-B	04315056+2424180	M1+M2	2.34	1, 5	cp+cs	30 (SiC)	10
B14	HN Tau A-B	04333935+1751523	K5+M4	3.11	2	cp+cs	65 (L)	3
B15	IS Tau A-B	04333678+2609492	K7+M4.5	0.22	8, 3	cp+cs	9 (L)	3
B16	IT Tau A-B	04335470+2613275	K3+M4	2.39	5	cp+cs	2.95 (SiC)	10
B17	RW Aur A-B	05074953+3024050	K1+K5	1.42	9, 5	cp+cs	13.63 (N)	10
B18	UY Aur A-B	04514737+3047134	K7+M2	0.88	1, 5	cp+cs	2.07 (N)	10
B19	V710 Tau A-B	04315779+1821380	M0.5+M2	3.17	2	cp	12.7 (SiC)	10
B20	V807 Tau A-B	04330664+2409549	K7+M3	0.3	4, 2, 3	cp	3.6 (L)	3
B21	V955 Tau A-B	04420777+2523118	K5+M1	0.33	3	cp+cs	5.6 (L)	3

♣The second spectral type, when available, is for the secondary star.

♠'cp' stands for circumprimary disk while 'cs' stands for circumsecondary disk. These disk configurations have been determined via resolved optical and infrared photometry, see Sect. 2 for details.

♦Flux ratios are calculated as primary/secondary. In parenthesis we provide the filter at which the flux ratio has been calculated (the SiC filter is centered at 11.8 μm , McCabe et al. 2006).

NOTE.—The 2MASS source name includes the J2000 sexagesimal, equatorial position in the form: hhmmssss+ddmmss (Cutri et al. 2003).

References. — (1) Leinert et al. 1993; (2) Hartigan et al. 1994; (3) White & Ghez 2001; (4) Cohen & Kuhl 1979; (5) Duchêne et al. 1999; (6) White et al. 1999; (7) White & Basri 2003; (8) Martin et al. 1994; (9) Mundt & Giampapa 1982; (10) McCabe et al. 2006

the 1-sigma standard deviation of the distribution of the data points.

The absolute flux calibration was done using order-based spectral response functions created within the *Formation and Evolution of Planetary Systems* (FEPS) Spitzer Legacy program (Hines et al. 2005; Meyer et al. 2006; Bouwman et al. 2007). The advantages of this spectral response function over the standard SSC bcd calibration are: a) the use of a larger number of calibrators from the FEPS program; b) the spectral response function is order and nod-position based; c) it is a 1D spectral response function allowing a better rejection of bad pixels. The estimated absolute flux calibration uncertainty is around 10% (Bouwman et al. 2007) and is propagated to the flux uncertainties assigned at each wavelength. The resulting calibrated spectra are available in the electronic edition of the *Astrophysical Journal* (Figs. 8, 9, 10, 11, 12, 13, 14 and 15).

We checked the absolute flux calibration of the IRS SL module using the published IRAC $8\mu\text{m}$ photometry by Hartmann et al. (2005) and Luhman et al. (2006), whose data have been acquired in two different campaigns, February–March 2004 and February 2005 respectively. Eleven sources have IRAC $8\mu\text{m}$ magnitudes from both campaigns, while 5 more sources have only magnitudes from February–March 2004 (Hartmann et al. 2005), and 14 more sources only from February 2005 (Luhman et al. 2006). The mean difference in the IRAC $8\mu\text{m}$ fluxes for the 11 sources observed in both campaigns is 16%, much larger than the IRAC absolute flux calibration accuracy of a few percent (Reach et al. 2005). The largest deviations are for FV Tau,

DL Tau, and DO Tau whose $8\mu\text{m}$ IRAC fluxes decreased by factors of 33%, 23%, and 23% respectively in a year baseline. These differences are likely due to intrinsic stellar variability. The IRS $8\mu\text{m}$ fluxes integrated over the IRAC $8\mu\text{m}$ spectral response curve agree on average within $\sim 10\%$ of the published IRAC photometry, which is within the estimated IRS flux calibration uncertainty. We also verified that our spectra very well agree with those published by Furlan et al. (2006) who adopted a different data reduction.

3.2. *Spitzer* 24 μm photometry

MIPS 24 μm (hereafter MIPS24) data are available in the *Spitzer* archive for all but 6 of the targets we selected (specifically DM Tau, DS Tau, GG Tau, HN Tau, RW Aur, and UY Aur). The majority of the MIPS data have been acquired as part of the Taurus *Spitzer* Legacy Program (PI D. Padgett) in February–March 2005 (id=3584) and March 2007 (id=30816) using the MIPS scan map operational mode. V710 Tau and GM Aur are not covered by these programs but have data from the c2d *Spitzer* Legacy Program (PI N. Evans, pid=173) and the GTO program respectively (PI G. Fazio, pid=37). We downloaded the post-bcd MIPS 24 μm products processed through the SSC pipelines S14.4.0 or later. In the case of photometry mode (only for V710 Tau), the SSC product is an averaged and registered single image while in the case of scan maps (for all other sources), the product is a distortion-corrected mosaic image³. The 24 μm post-bcd images generated from pipeline ver-

³<http://ssc.spitzer.caltech.edu/mips/dh/mipsdatahandbook3.2.pdf>

TABLE 3

FLUXES AT $24\mu\text{M}$ FROM MIPS IMAGES (THIRD COLUMN, F24) OR AT $25\mu\text{M}$ FROM IRS SPECTRA (FOURTH COLUMN, F25). THE ABSOLUTE PHOTOMETRIC UNCERTAINTY IS EXPECTED TO BE $\sim 10\%$. THIS UNCERTAINTY INCLUDES BOTH THE INTERNAL RANDOM AND THE ABSOLUTE CALIBRATION UNCERTAINTY, SEE TEXT FOR DETAILS.

#	Source	F24 [mJy]	F25 [mJy]	Comment
S1	AA Tau	525	...	
S2	BP Tau	666	...	
S3	CI Tau	997	...	
S4	CW Tau	1445	...	
S5	CX Tau	296	...	
S6	CY Tau	123	...	
S7	DE Tau	677	...	
S8	DH Tau	316	...	
S9	DL Tau	965	...	
S10	DM Tau	...	320	no MIPS24
S11	DN Tau	424	...	
S12	DO Tau	...	2951	MIPS24 saturated
S13	DP Tau	1281	...	
S14	DS Tau	...	303	no MIPS24
S15	FM Tau	462	...	
S16	FN Tau	1047	...	
S17	FZ Tau	1057	...	
S18	GI Tau	1006	...	
S19	GK Tau	...	1699	MIPS24 saturated
S20	GM Aur	746	...	
S21	IP Tau	277	...	
S22	IQ Tau	544	...	
S23	LkCa 15	398	...	
B1	CoKu Tau3	327	...	
B2	CZ Tau	1232	...	
B3	DD Tau	1575	...	
B4	DF Tau	945	...	
B5	DK Tau	1286	...	
B6	FO Tau	529	...	
B7	FS Tau	...	2112	MIPS24 saturated
B8	FV Tau	...	2344	MIPS24 saturated
B9	FX Tau	420	...	
B10	GG Tau	...	1266	no MIPS24
B11	GH Tau	379	...	
B12	GN Tau	536	...	
B13	HK Tau	823	...	
B14	HN Tau	...	2988	no MIPS24
B15	IS Tau	228	...	
B16	IT Tau	264	...	
B17	RW Aur	...	2012	no MIPS24
B18	UY Aur	...	5918	no MIPS24
B19	V710 Tau	245	...	
B20	V807 Tau	476	...	
B21	V955 Tau	546	...	

sions later than S14 have improved flat field corrections and are suitable for photometry at an accuracy of 10% (Sect. 9.1 of the MIPS Data Handbook v 3.2, link in footnote 3), sufficient for the purposes of this study.

Aperture photometry was done using IDP3 (Schneider & Stobie 2002). The centroid of the aperture was found by fitting a Gaussian to each source. We used an aperture radius of $6''.6$ (2.7 pixels) and background annulus from $20''$ to $32''$. We opted for this intermediate aperture radius among those suggested by the Spitzer Science Center to include the emission from both binaries (as in the IRS spectra) and to exclude the emission from companions at $>10''$ from some of the single stars (see, note to Table 1). To recover the total flux we then applied the proper aperture correction of 1.648⁴. DO Tau, GK Tau, FS Tau, and FV Tau have $24\mu\text{m}$ fluxes $\geq 1.6\text{ Jy}$ and are thus saturated in the 3sec exposures acquired within the Taurus *Spitzer* Legacy Program. For these sources as well as for the 6 targets that lack MIPS24 data, we computed the $25\mu\text{m}$ flux (integrated flux from 23.5 to $26.5\mu\text{m}$) from our SL $6\mu\text{m}$ flux and the n_{6-25} spectral indices from Table 4 of Furlan et al. (2006)⁵. We will show in Sect. 4.2 that our results are not affected by the use of $25\mu\text{m}$ fluxes instead of $24\mu\text{m}$ fluxes for these 10 objects. For the sources that have both MIPS24 observations and LL data we find that our aperture photom-

etry agrees within about 10% with the IRS $24\mu\text{m}$ flux integrated over the MIPS24 spectral response curve. Table 3 summarizes the MIPS24 or the IRS25 fluxes for our sample of single and binary systems.

4. Results

4.1. Strength and Shape of the $10\mu\text{m}$ Feature

The $10\mu\text{m}$ silicate emission feature traces silicate dust in the optically thin layer of circumstellar disks out to about 1 AU from a star with solar luminosity (e.g. Kessler-Silacci et al. 2007). Because the smaller the grain the longer its timescale to settle to the disk midplane, the $10\mu\text{m}$ feature probes the population of the smallest grains in a disk, up to a few micron in size. The strength and shape of the feature bear information on the amount of processing that dust grains have undergone in the disk. In particular, the flux ratio of normalized spectra at 11.3 (or 8.6) over $9.8\mu\text{m}$ can be used as a proxy for the degree of crystallization while the peak-to-continuum ratio can be used as a proxy for grain growth (e.g. Bouwman et al. 2001; van Boekel et al. 2005; Apai et al. 2005; Bouwman et al. 2007). We use these band strengths to search for differences in the dust processing of single and binary systems.

We first fit a third-order polynomial⁶ to the spectral data outside the $10\mu\text{m}$ sili-

⁴<http://ssc.spitzer.caltech.edu/mips/apercorr/>

⁵most of these sources are so bright that were observed only with the IRS high-resolution module. Therefore we could not compute $24\mu\text{m}$ fluxes from the LL data we reduced

⁶A third order polynomial gives smaller residuals in the spectrum minus fitted continuum than a first, a second, or a fourth order polynomial. We also verified that the results discussed in this section do not change when using lower or higher order polynomials to fit the continuum.

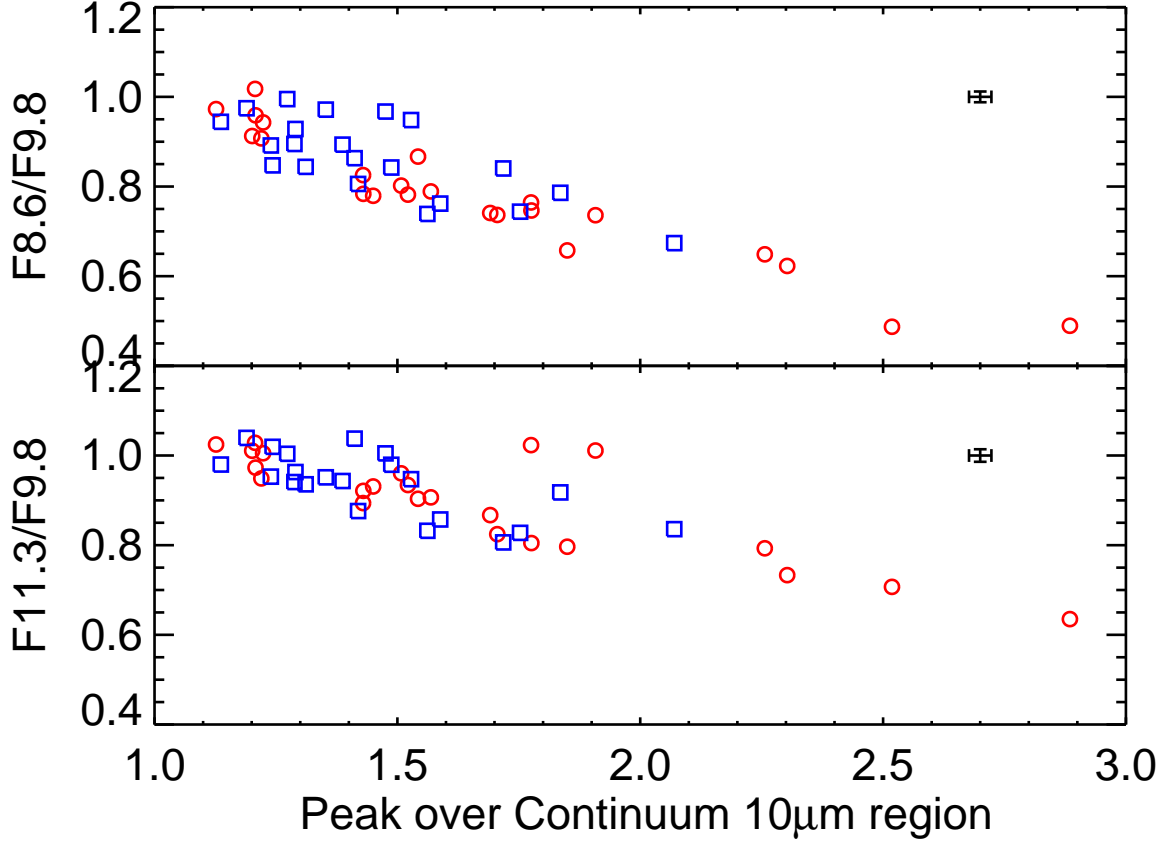


Fig. 2.— Strengths and shapes of the $10\,\mu\text{m}$ silicate emission features for the sample of single (red circles) and binary (blue squares) systems. On the y-axis we plot the ratios of the normalized flux at 8.6 and $11.3\,\mu\text{m}$ over $9.8\,\mu\text{m}$, which are proxies for the degree of crystallinity. The x-axis gives the peak over continuum in the $10\,\mu\text{m}$ region of normalized spectra, which indicates the amount of grain growth. Objects with processed dust are located on the top left of the diagram. Average error bars are shown on the right upper corner of each plot (see Sect. 4.1 for details).

cate emission feature (between 6 and $8\,\mu\text{m}$ and between 12 and $14\,\mu\text{m}$) and then normalize our spectra to the fitted continuum. This normalization ensures that the shape of the spectral features remains identical to the original one (e.g. van Boekel et al. 2005). Fig. 2 shows the band strengths for our sample of single (red circles) and multiple (blue squares) systems. The flux densities at 8.6, 9.8, and $11.3\,\mu\text{m}$ are the mean values of flux densities within $\pm 0.1\,\mu\text{m}$ of these wavelengths. To analyze the uncertainties we followed a Monte Carlo approach. For each disk we added a normally distributed noise to the spectrum and computed the peak-over-continuum and flux ratios 500 times. Their standard deviation gives the uncertainty on the peak-over-continuum and flux ratios for each target. The error bars in Fig. 2 are the average uncertainties. The simulated noise had two components: i) a normally distributed noise at each wavelength with an amplitude equal to the flux uncertainty at that wavelength; ii) a random calibration uncertainty (equal at all wavelengths) with an amplitude of 10%.

Objects on the bottom right side of Fig. 2 have $10\,\mu\text{m}$ emission features similar to the ISM absorption feature, thus their dust grains have experienced little processing. Conversely, objects on the top left side of the plot have disks with larger grains (micron in size) and crystals. There is an obvious anticorrelation between the strength of the $10\,\mu\text{m}$ silicate emission feature and the F11.3/F9.8 (or F8.6/F9.8) flux ratios, which is apparent not only in Fig. 2 but also in other similar plots in the literature (e.g. van Boekel et al. 2005; Apai et al. 2005). We use the Kendall's τ

test to measure the degree of anticorrelation. This nonparametric test uses the relative rank ordering of pairs of data to compute two values (see e.g. Press et al. 1993): the rank correlation coefficient τ which runs between -1 (complete rank reversal) and 1 (complete rank agreement), and the two-sided probability P that the variables are uncorrelated ($\tau = 0$). For the single stars in Fig. 2 (circles), Kendall's $\tau = -0.8$ and $P = 6 \times 10^{-8}$ for the F8.6/F9.8 flux ratio versus the peak-over-continuum while $\tau = -0.6$ and $P = 2 \times 10^{-5}$ for the F11.3/F9.8 flux ratio versus the peak-over-continuum. For the binary stars in Fig. 2 (squares), Kendall's $\tau = -0.5$ and $P < 0.001$ for the F8.6/F9.8 and the F11.3/F9.8 flux ratios versus the peak-over-continuum. We interpret these trends as confirmation that there is a significant anticorrelation between the strength of the silicate emission features and the flux ratios presented in Fig. 2. Therefore, both the peak-over-continuum and the F11.3/F9.8 (or F8.6/F9.8) flux ratios provide an analogue measurement of dust processing in circumstellar disks.

The main question we want to answer in this paper is whether the population of disks around single stars statistically differ in terms of dust processing from the population of disks around binaries. In other words, do either of the two populations have more processed dust in their disks than the other? To answer this question we apply the Kolmogorov–Smirnov (hereafter K–S) test (see, e.g. Press et al. 1993) and the Mann–Whitney U (hereafter MWU) test (see, e.g. Ronald & Raymond 1985) on the peak-over-continuum and the flux ratios (F11.3/F9.8 and F8.6/F9.8) pre-

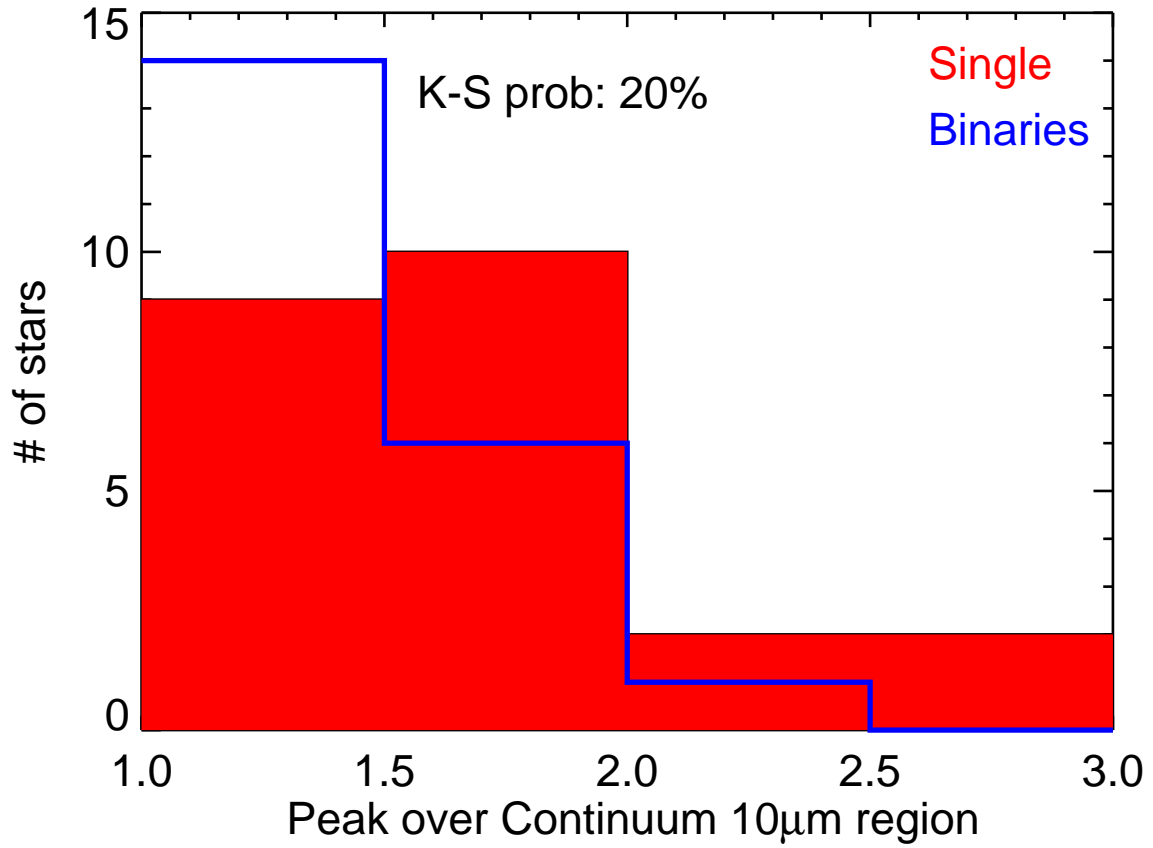


Fig. 3.— Histogram of the $10\,\mu\text{m}$ feature strengths for the single (red) and binary (blue) systems. The K–S test indicates that the two distributions are consistent with having been drawn from the same parent population. This suggests that the growth of grains up to a few micron in size is not affected by the presence of a medium–separation stellar companion.

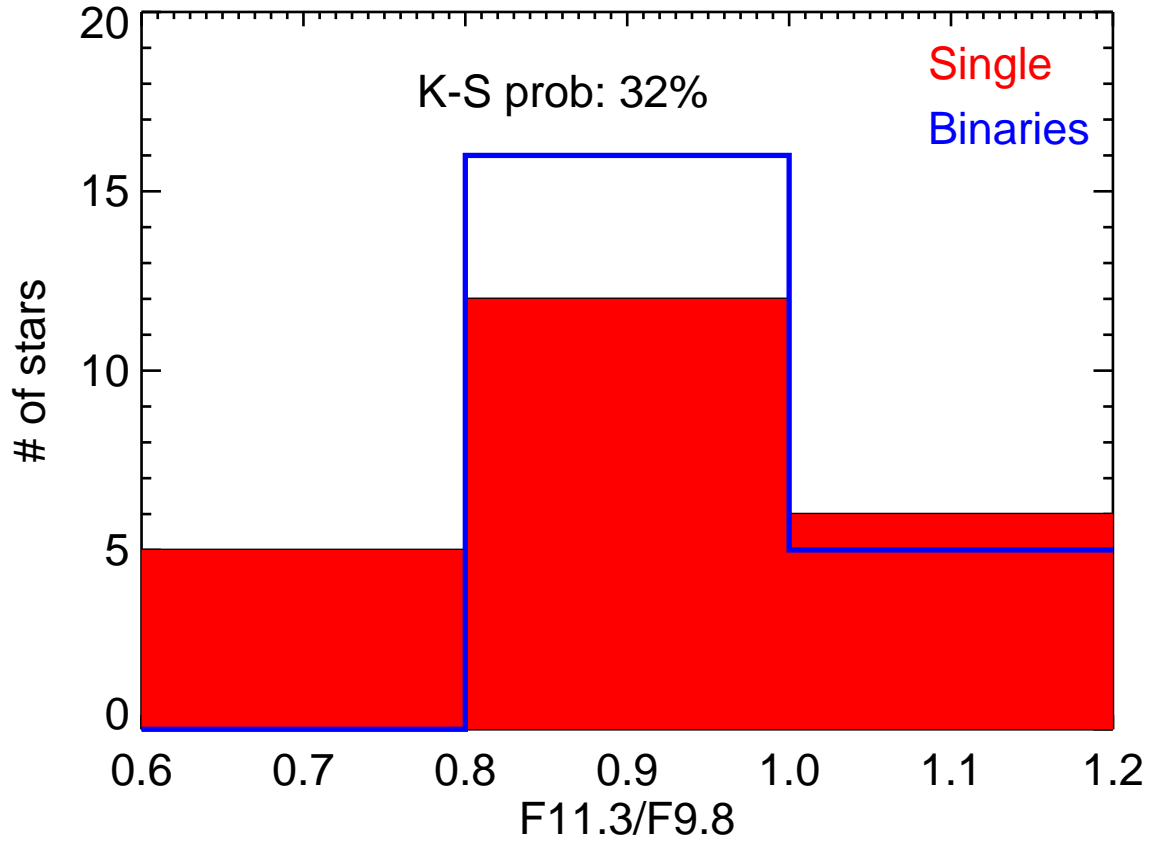


Fig. 4.— Histogram of the flux ratios at 11.3 over $9.8\,\mu\text{m}$ for the single (red) and binary (blue) systems. The K–S test does not indicate that the two distributions differ statistically. This suggests that crystalline processing is not influenced by the presence of stellar companions at tens of AU.

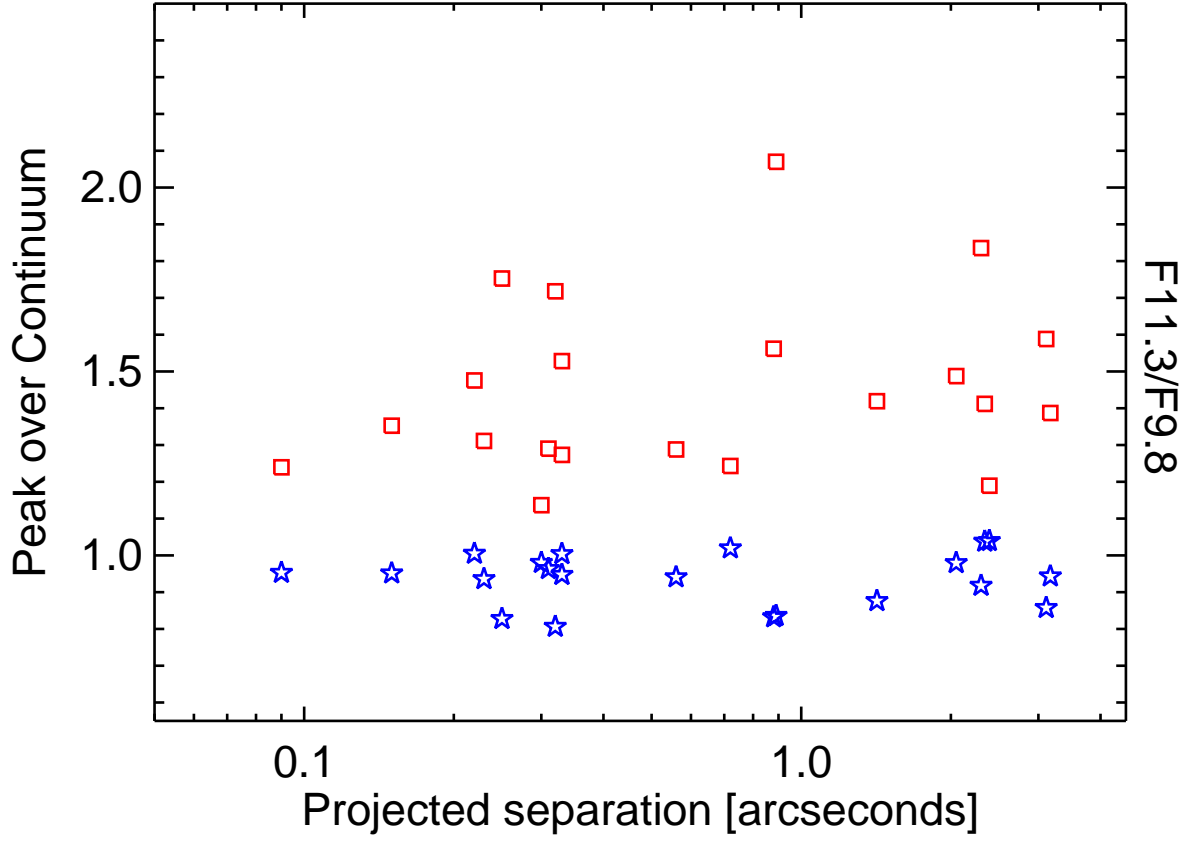


Fig. 5.— Strength (squares) and shape (stars) of the $10\,\mu\text{m}$ silicate emission feature versus projected binary separation. The peak-over-continuum compared to the projected separation (squares) gives a Kendall's $\tau=0.1$ and $P=0.4$ suggesting that these variables are not correlated. Similarly, the F11.3/F9.8 flux ratio is uncorrelated with the binary projected separation (stars) as indicated by a Kendall's $\tau=0.02$ and $P=0.9$.

sented in Fig. 2. The K–S and the MWU tests are both non-parametric tests with the null hypothesis that two samples are drawn from a single population and work on unbinned data. Because the K–S test gives large probabilities of 0.2 for the peak-over-continuum of single and binaries and 0.3 for their F11.3/F9.8 (and F8.6/F9.8) flux ratios, we conclude that both samples could have been drawn from the same distribution. Similarly the MWU test does not reveal any statistically significant difference in the degree of grain growth and crystallinity of the single and binary samples: the probability that both distributions were drawn from the same parent population for the peak-over continuum is 0.08 while for the flux ratios F11.3/F9.8 (and F8.6/F9.8) is 0.1. Figs. 3 and 4 provide a visualization of the peak-over continuum and F11.3/F9.8 flux ratio distributions for the samples of disks around single and binary stars. Further supporting our conclusion, Fig. 5 shows no clear trend of the strength (or shape) of the $10\,\mu\text{m}$ feature with the projected separation of the companion. Kendall’s τ are close to 0 and P are large for the rank ordering of peak-over-continuum (or F11.3/F9.8) compared to the projected separation (see caption of Fig. 5) suggesting that the variables are uncorrelated.

4.2. Dust settling

Coagulation models show that if the dust grains in the upper layers of a flared disk become sufficiently large, they will gravitationally settle towards the mid-plane of the disk, resulting in a flattened disk geometry (e.g. Schr ppler & Henning 2004; Nomura & Nakagawa 2006). Thus

a way to search for grain growth is to evaluate the flaring of circumstellar disks. While the shape of the $10\,\mu\text{m}$ feature is sensitive to the presence of grains of a few microns in size in the disk upper layer the disk flaring should probe the overall grain population of larger grains (e.g. Dullemond & Dominik 2004). To evaluate the disk flaring we use the ratio of fluxes at two different mid-infrared wavelengths. This procedure is justified by two facts: a) the continuum flux emitted from the surface layer of the disk becomes proportional to the disk flaring at radial distances from solar-type stars of 0.4 AU or larger (Chiang & Goldreich 1997) and b) these radial distances are probed by mid-infrared observations.

We integrate the flux of our SL infrared spectra in two wavelength bands one shortward and one longward of the $10\,\mu\text{m}$ silicate emission feature: $5.4\text{--}6.0\,\mu\text{m}$ (central wavelength $5.7\,\mu\text{m}$) and $12.5\text{--}14.0\,\mu\text{m}$ (central wavelength $13.25\,\mu\text{m}$). In addition, we use the MIPS24 photometry (or the IRS25 flux when MIPS is not available, see Table 3) to trace the disk flaring out to a few AU from the central star. The calculated flux ratios are shown in Fig. 6 and histograms are presented in Fig. 7. Larger flaring is indicated by higher ratios of long-wavelength continuum to short-wavelength continuum flux from the dust disk. These plots show that both single and binary systems have a large variety of disk structures with no preference for any structure in the two samples. The K–S and the MWU probabilities that the the flux ratio distributions for single and binary stars come from the same parent population are higher than 0.1 confirming

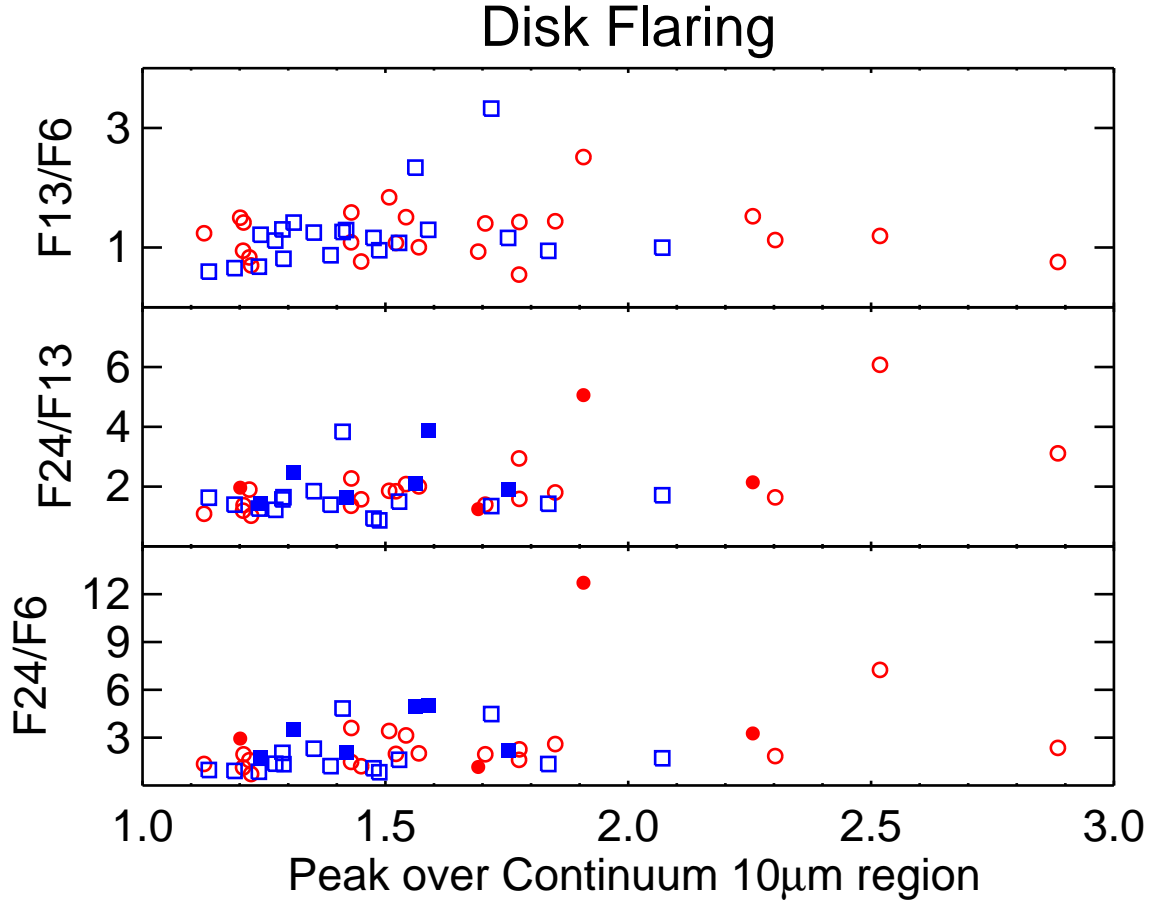


Fig. 6.— Flux ratios at 13.25 over 5.7 μm (top), at 24.0 over 13.25 μm (middle), and at 24.0 over 5.7 μm (bottom) versus the peak-over-continuum in the 10 μm feature. These ratios are a proxy for the disk flaring; more flaring is indicated by larger ratios in the figure. Squares represent binaries, while circles indicate single stars. Filled symbols are for those sources that do not have MIPS24 photometry or are saturated in the MIPS exposures. For these sources we plot the IRS25 flux computed as described in Sect. 3.2. Both single and binary systems have a large variety of disk structures.

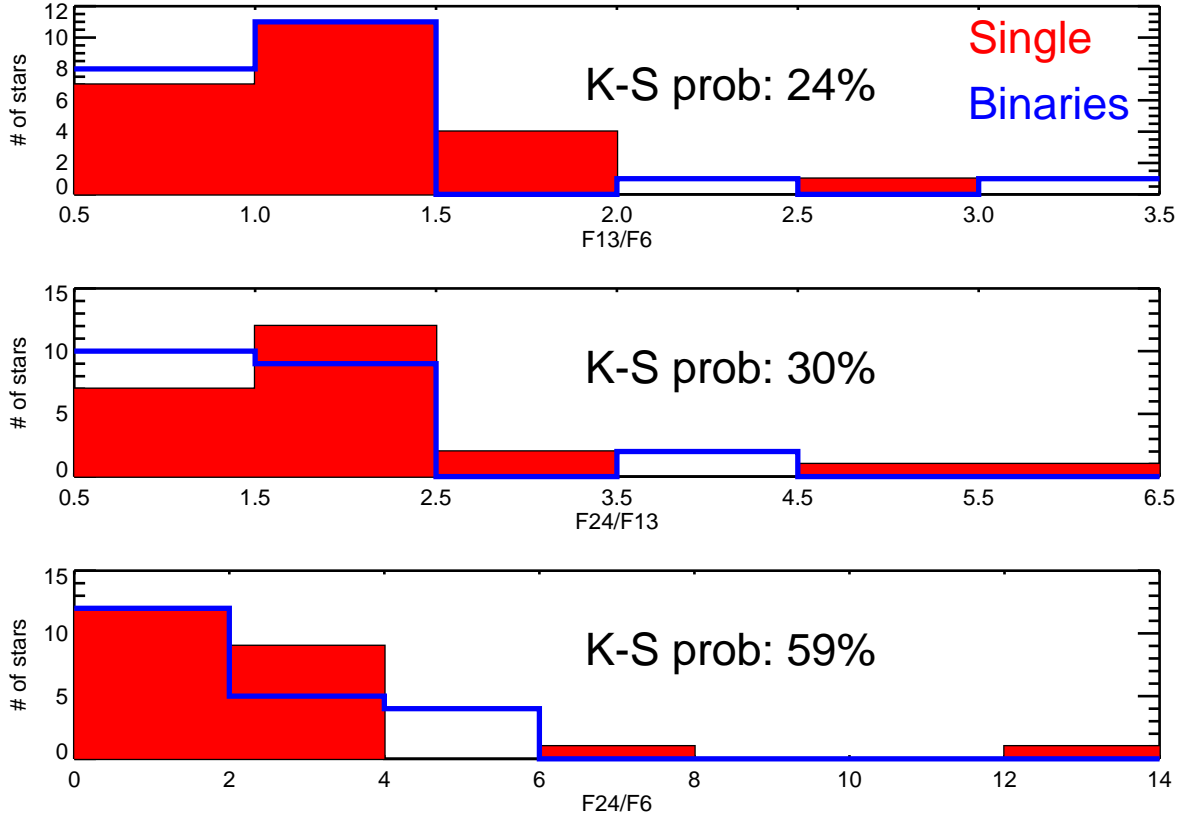


Fig. 7.— Histograms for the flux ratios at 13.25 over $5.7\,\mu\text{m}$ (top), at 24.0 over $13.25\,\mu\text{m}$ (middle), and at 24.0 over $5.7\,\mu\text{m}$ (bottom) for the single (red) and binary (blue) systems. The distributions of flux ratios (disk flaring) do not differ statistically according to the K-S and the MWU tests. MWU probabilities are 0.22, 0.13, and 0.18 for the F_{13}/F_6 , F_{24}/F_{13} , and F_{24}/F_6 respectively.

that the distributions of disk flaring for the two samples are not statistically different (the same result holds when excluding the sources with IRS25 fluxes).

5. Discussion

Our study shows a large diversity in the $10\mu\text{m}$ silicate emission features and SED slopes of T Tauri disks. We found that neither the dust processing nor the disk flaring correlates with the multiplicity of the sources. These results are particularly interesting for two aspects that will be discussed in the following.

5.1. Medium-separation binaries and planet formation

A stellar companion induces tidal forces in a disk that become particularly strong at resonance points. Resonant interactions result in the excitation of density waves that can truncate a disk and act to modify the binary eccentricity (see e.g. Lubow & Artymowicz 2000 for a review). Theoretical calculations of binary-disk interactions predict that circumstellar disks will be truncated at 0.2–0.5 times the binary semimajor axis a , with the exact values depending on eccentricity, mass ratio, and disk viscosity (Artymowicz & Lubow 1994). These theoretical expectations are supported by millimeter observations of binaries tracing the optically thin dust emission and thus the total disk mass in the system. There is evidence for a diminished millimeter flux (hence disk mass) among the 1–100 AU binaries in comparison to wider binaries or single stars (e.g. Mathieu et al. 2000 for a review). This result is qualitatively consistent with the circumstellar disks of medium-separation bi-

aries being tidally truncated at 0.2–0.5 a . Two-thirds of our sources have stellar companions between 0.1''–1'', with a mean projected separation of 0.4'' or 56 AU at the distance of Taurus. Therefore, the typical truncation radius for disks in our sample is >11–28 AU, well outside the location of Jupiter and Saturn in our Solar System. Even in other systems these outer radii are found to be devoid of giant planets (e.g. Kasper et al. 2007). This fact suggests that the formation of terrestrial and giant planets may proceed undisturbed in disks around medium-separation binaries even if these disks are constrained in size.

Early investigations of young TTSSs found no significant difference in the frequency of near- and mid-infrared excess emission between single and binary star systems (e.g. Simon & Prato 1995; Jensen et al. 1996). With the $60\mu\text{m}$ IRAS flux probing dust $\lesssim 10$ AU from the central star, these measurements demonstrate that binary systems as often have disks as single stars do. Recently Monin et al. (2007) analyzed the separation distributions of binaries with and without disks and found no statistical difference. Since most of their binaries have projected separations >20 AU, their result shows that medium- and wide-separation binaries do not have a significant effect on the circumstellar disk lifetime. Our work indicates that these disks also evolve in a similar way. The extent of dust processing in the disk surface layer and the degree of dust settling in binary disk systems do not statistically differ from those in disks around single stars. This suggests that the first few Myr of disk evolution in the terrestrial (and maybe out

to the giant) planet-forming region are not affected by medium-separation stellar companions. Whether the disk evolution proceeds undisturbed for tens of millions of years until planets are fully formed cannot yet be assessed observationally. Bouwman et al. (2006) estimate a mean disk dispersion timescale of ~ 5 Myr for close (≤ 4 AU) binaries in contrast to a timescale of ≈ 9 Myr for single star systems. They argue that the time available to form planets in close binary systems is considerably shorter than that in disks around single stars, which may inhibit planet formation. The only two medium-separation binaries in their sample hint for a disk dispersal timescale comparable to that of single stars suggesting a similar disk evolution for single and medium-separation binary systems over the first ~ 10 Myr.

Exoplanet surveys offer us a glimpse into the frequency and properties of giant planets in multiple star systems. Recently Eggenberger & Udry (2007) reported 42 planets orbiting binary and multiple stars (see, their Table 1). Bonavita & Desidera (2007) analyze a subsample of radial velocity planet host stars with uniform planet detectability and demonstrate that the overall frequency of giant planets in binaries is not statistically different from that of planets in single stars. However, they find indications for a lower frequency of radial velocity planets in the subgroup of close- and medium-separation binaries ($< 50 - 100$ AU). In a complementary study, Desidera & Barbieri (2007) find that the mass distribution of planets in binaries with separations $< 300 - 500$ AU is statistically different from that around wider binaries and single stars: Massive

planets in short-period orbits are found predominantly around close- and medium-separation binaries. Taken together, the results from the frequency and properties of exoplanets suggest that a stellar companion with separation less than a few hundred AU affects giant planet formation and/or the subsequent migration. Numerical simulations seem to support this notion. Kley (2000) shows that a fairly eccentric ($e_{\text{bin}} = 0.5$) stellar companion at 50–100 AU enhances the growth rate of a Jupiter mass planet embedded in a circumstellar disk and makes its inward migration more rapid. Recently, Kley & Nelson (2007) confirm these trends by following the evolution of a $30 M_{\oplus}$ protoplanet in a disk truncated by a stellar companion at 18.5 AU and $e_{\text{bin}} = 0.36$, like the γ Cep binary system. Our study shows that the early evolution of protoplanetary disks surrounding binary stars is similar to that in single stars indicating that the differences in the exoplanet properties arise in the later stages of their formation and/or migration.

Whether terrestrial planet formation is also affected by medium-separation binaries cannot be yet addressed observationally. Our study shows that the initial dust processing is not impacted by the presence of a stellar companion. Based on the fact that the build-up of planetesimals as large as the ~ 500 -km Vesta has occurred in the first 3.8 ± 1.3 Myr of the Solar nebula (Kleine et al. 2002), it is reasonable to speculate on the basis of our study that the formation of planetesimals in binary and single systems proceed along, if not on identical avenues. Another indication supporting this sugges-

tion comes from the finding of a similar incidence of debris disks in Gyr-old single and binary stars (Trilling et al. 2006). If the debris dust is produced by colliding asteroids, then the similar rate of debris dust in binaries implies that planetesimal formation is not inhibited by the presence of stellar companions. Recent simulations of the later stages of terrestrial planet formation show that rocky planets can form in a wide variety of binary systems (Quintana & Lissauer 2007). The binary periastron is the most important parameter in limiting the number of forming planets and their range of orbits. Quintana & Lissauer (2007) show that binaries with periastron $\gtrsim 10$ AU, comprising most of the medium-separation binaries investigated in this paper, can form terrestrial planets over the entire range of orbits allowed for single stars. As a result more than 50% of the binary systems in the Milky Way (Duquennoy & Mayor 1991) are wide enough to allow the formation of Earth-like planets.

5.2. The diversity in silicate features and SEDs

Although small sample statistics suggested a correlation between stellar multiplicity and initial dust processing (Meeus et al. 2003; Sterzik et al. 2004; Sicilia-Aguilar et al. 2007), our study demonstrates that medium-separation stellar companions do not appreciably affect the growth and crystallization of dust in circumstellar disks. Given the criteria applied to select our samples, we can also exclude that age, spectral type, and stellar environment can account for the large variety of observed silicate emission features and SED slopes in our study.

There may be several other factors contributing to this diversity that will be fully explored in an upcoming contribution. In the following we briefly mention two of them:

Turbulence in circumstellar disks not only drives the accretion of gas onto the central star but also replenishes the disk atmosphere with more grains that can be larger in size. If the grains inferred from the $10\,\mu\text{m}$ silicate emission feature reflect the level of disk turbulence, the strength of the features should depend on the stellar accretion rates. Sicilia-Aguilar et al. (2007) note that stars with strong features tend to have large accretion rates in their sample of several Myr old intermediate- and low-mass stars. This trend may be the result of turbulence determining the grain population in the disk atmosphere. Alternatively, the trend could be due to the more massive stars (that have typically larger accretion rates) in their sample heating larger disk area and thus producing stronger silicate emission features (see, e.g. Kessler-Silacci et al. 2007). The tentative correlation seen in the sample of Sicilia-Aguilar et al. (2007) needs to be confirmed using a larger and more homogeneous sample of stars with well-determined accretion rates.

Different initial conditions for the collapsing cores may also leave their imprints on the formation and evolution of circumstellar disks. This possibility has been explored by Dullemond et al. (2006) to explain crystallization of dust grains in the early stages of disk evolution. In their model the level of crystallinity depends crucially on the rotation rate of the collapsing cloud core because this determines the

radius at which the infalling matter reaches the disk: rapidly rotating clouds would evolve into disks with low crystallinity, while slowly rotating clouds into disks with high crystallinity.

6. Summary

In this paper we explored the effect of a stellar companion on the initial growth and settling of dust grains in circumstellar disks. We constructed two large samples of disks around single and binary TTSs with a narrow age spread and a spectral type distribution for the single stars identical to that of the primary stars in the binary sample. We used the strength of the $10\,\mu\text{m}$ silicate emission feature derived from IRS/*Spitzer* spectra as a proxy for grain growth and the SED slope of circumstellar disks as a proxy for dust settling. Our results can be summarized as follows:

- there is no statistically significant difference between the distribution of $10\,\mu\text{m}$ silicate emission features from single and binary systems.
- the distribution of disk flaring is indistinguishable between the single and binary system samples.

These results show that stellar companions at projected separations of $\gtrsim 10\,\text{AU}$ do not appreciably affect the degree of crystallinity nor the degree of grain growth. Based on the combination of these and other results we argue that the formation of planetesimals and possibly terrestrial planets is not inhibited in a circumstellar disk perturbed by a medium-separation stellar companion.

This work is based on observations made with the Spitzer Space Telescope,

which is operated by the Jet Propulsion Laboratory, California Institute of Technology. We are pleased to acknowledge support through NASA contract 1290778 and through the NASA Astrobiology Institute. We thank D. Padgett, PI of the *Spitzer* Legacy team mapping the Taurus Molecular Cloud, for providing such a valuable dataset to the star and planet formation community. We thank the anonymous referee for thoughtful comments that helped to improve the manuscript.

Facilities: Spitzer Space Telescope

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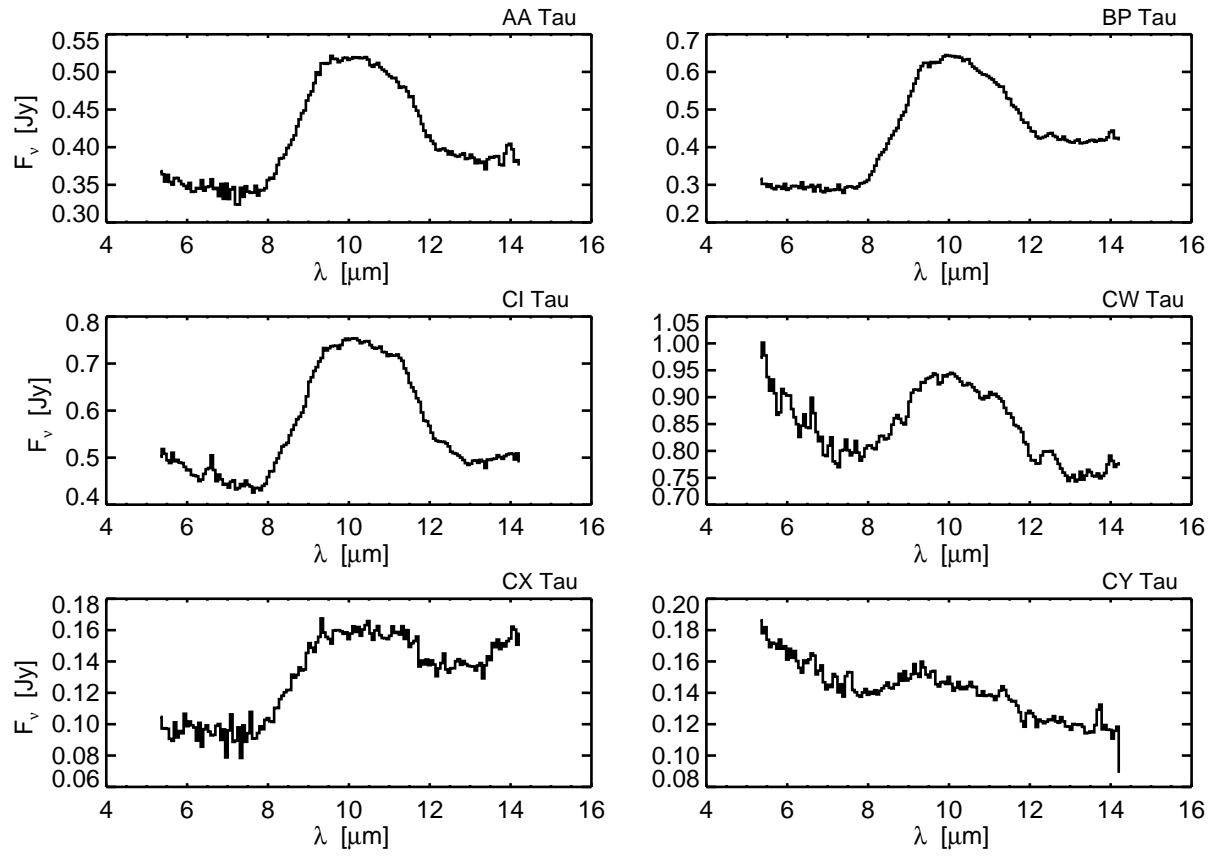


Fig. 8.— Infrared spectra for the sample of single stars.

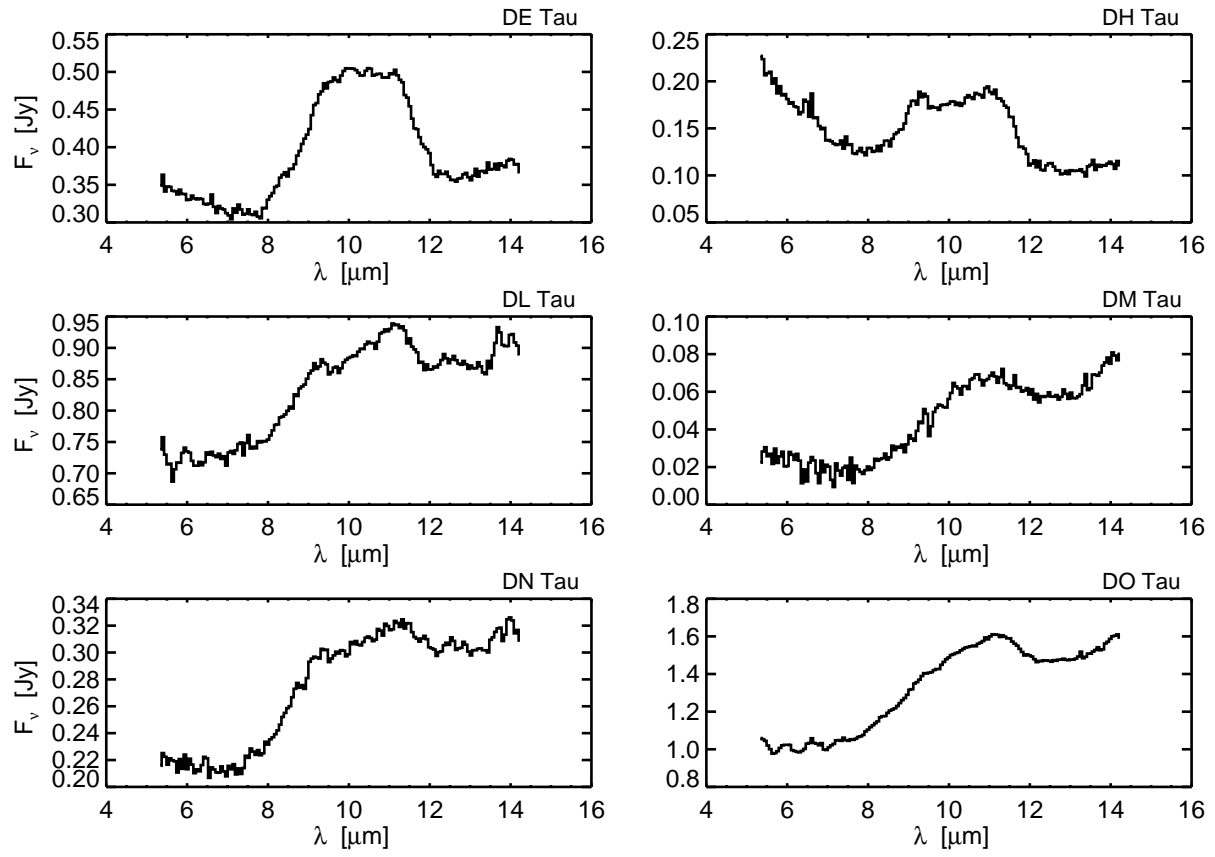


Fig. 9.— Infrared spectra for the sample of single stars.

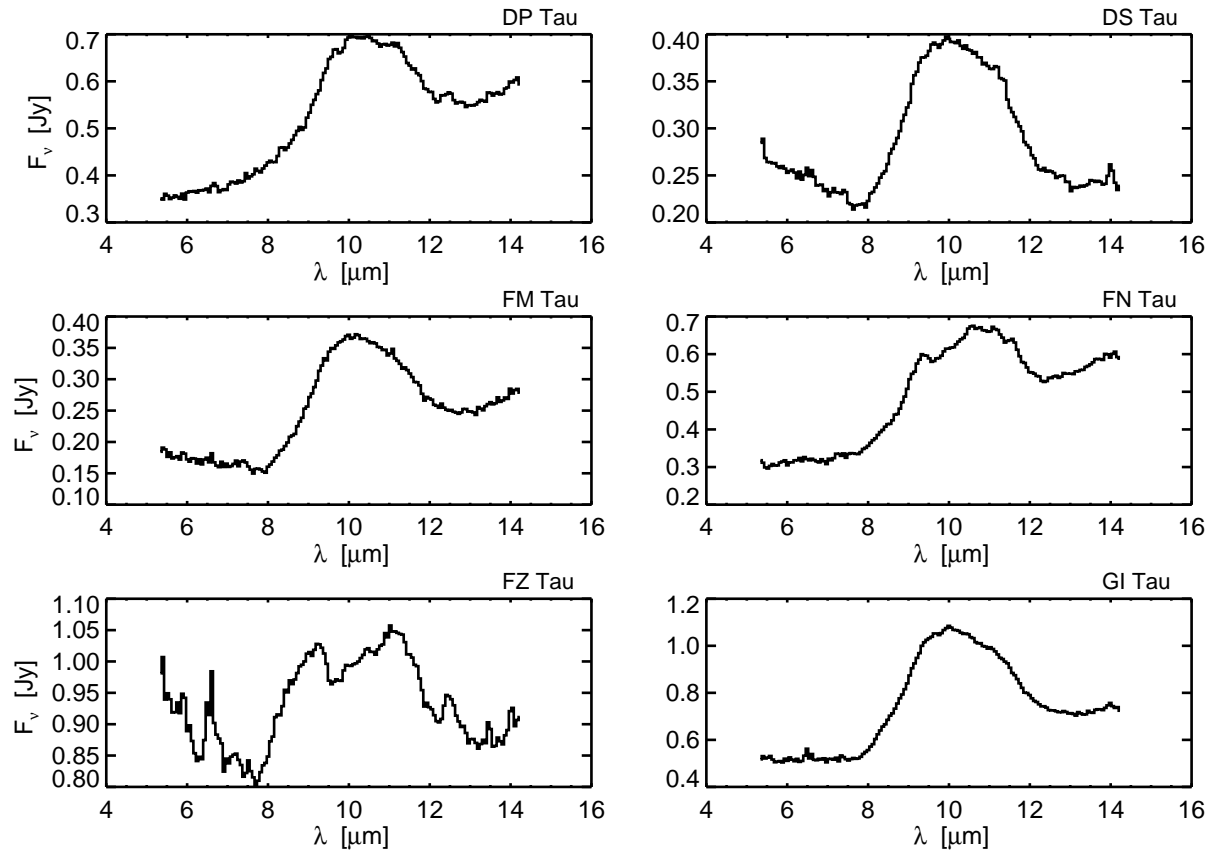


Fig. 10.— Infrared spectra for the sample of single stars.

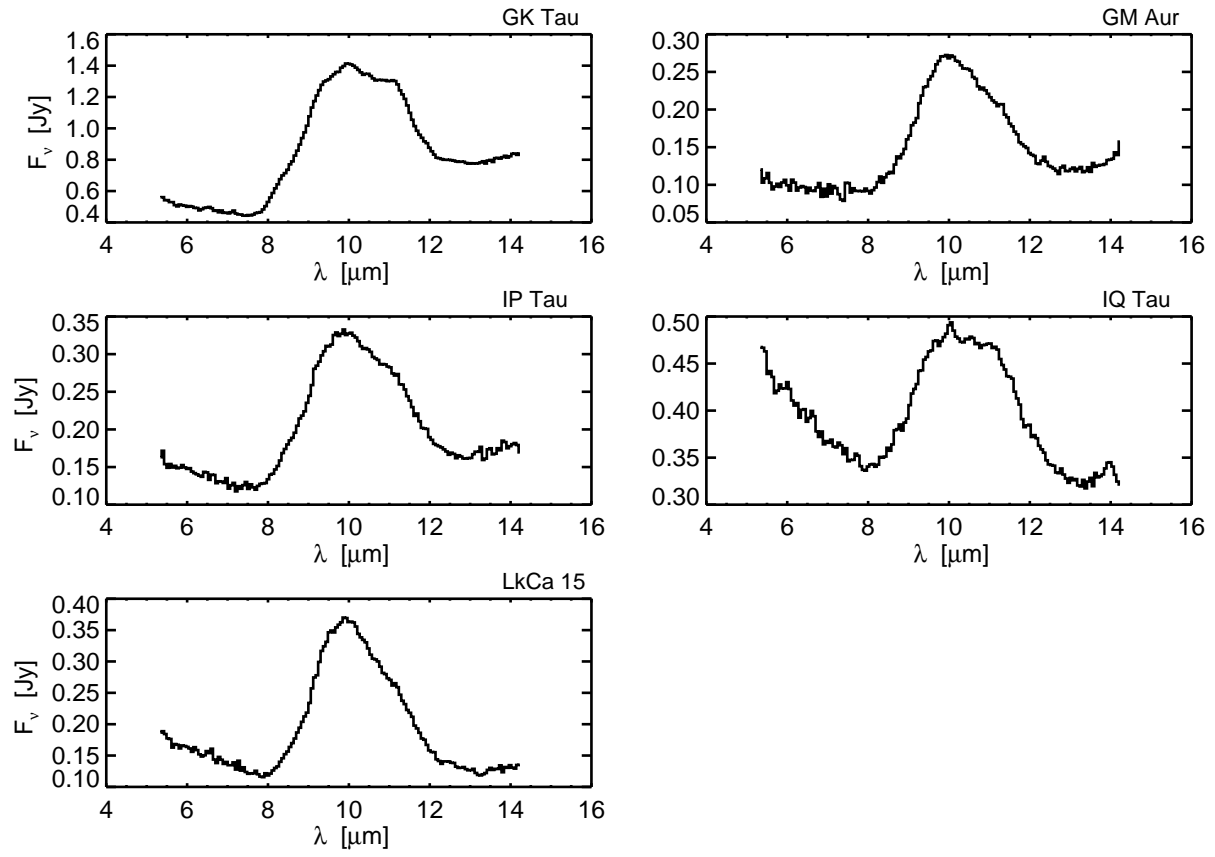


Fig. 11.— Infrared spectra for the sample of single stars.

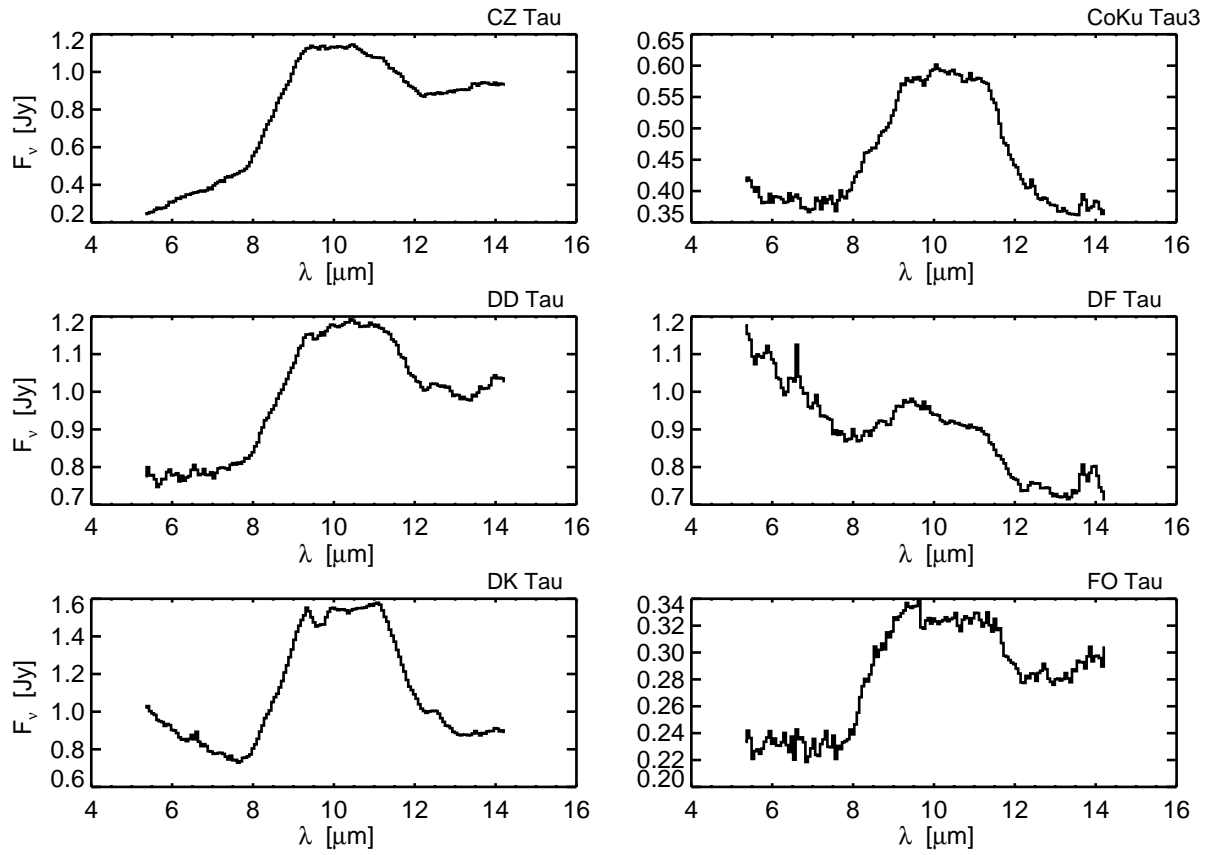


Fig. 12.— Infrared spectra for the sample of binary stars.

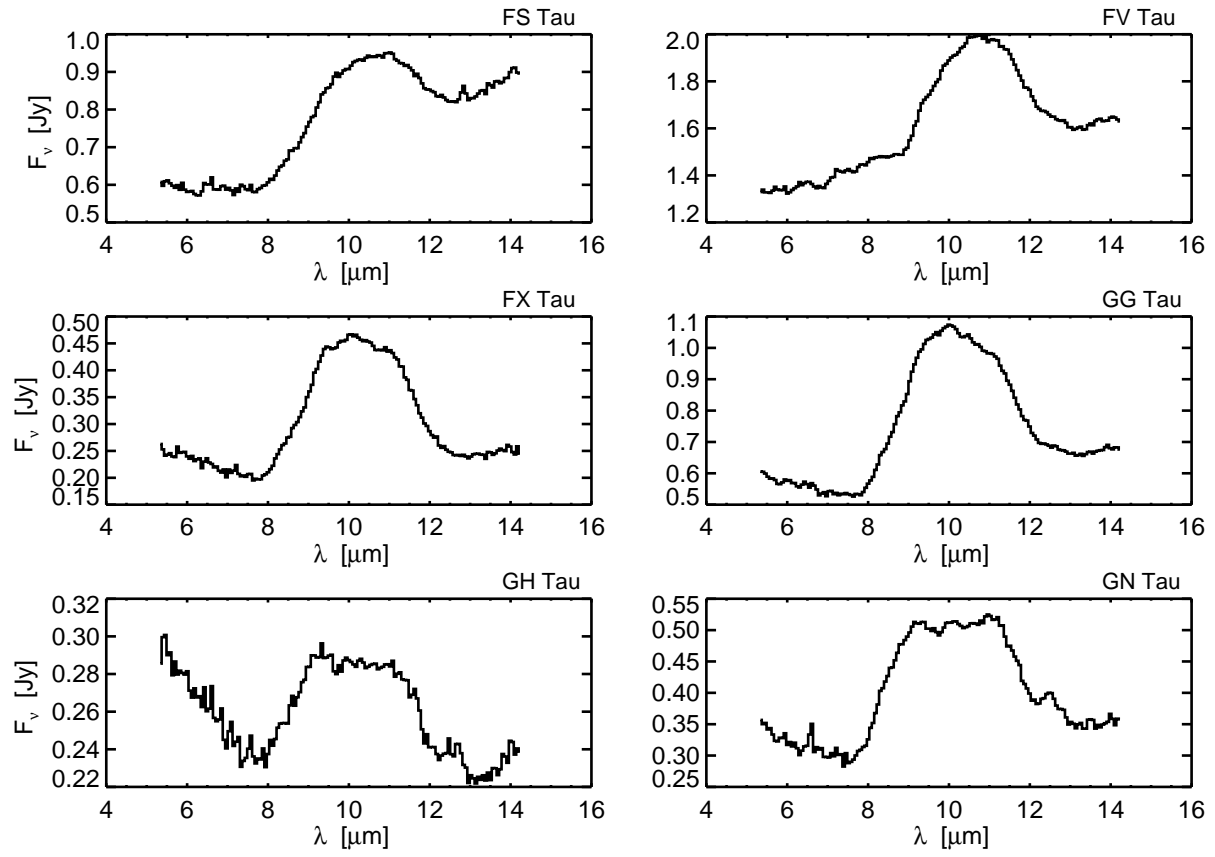


Fig. 13.— Infrared spectra for the sample of binary stars.

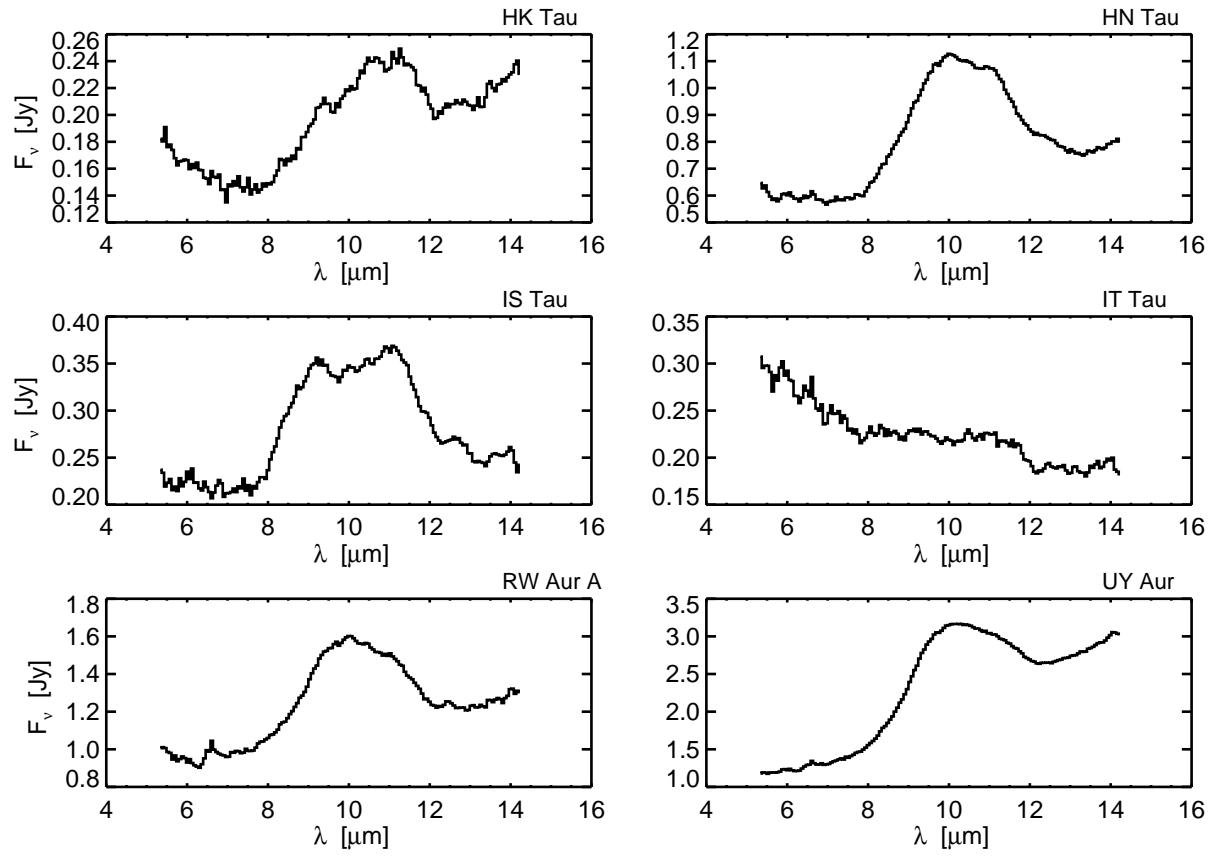


Fig. 14.— Infrared spectra for the sample of binary stars.

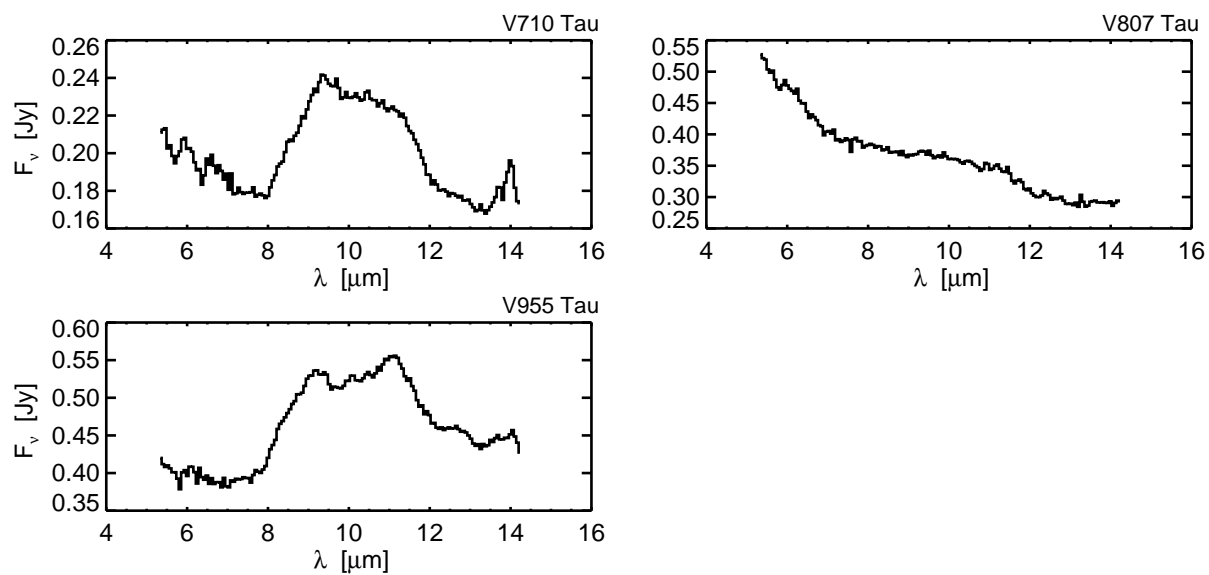


Fig. 15.— Infrared spectra for the sample of binary stars.

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